HIGH CONDUCTIVITY COPPER ALLOYS

CADMIUM COPPER
CHROMIUM COPPER
SILVER COPPER
TELLURIUM COPPER

A C.D.A. PUBLICATION

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Fig. 1. Making motor car radiators from silver copper strip.

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FOREWORD

This booklet forms one of a series of technical publications offered by the Copper Development Association for the guidance of users of copper and copper alloys. It deals with four alloys which have achieved considerable importance in the electrical industries and in applications involving the transfer of heat. All four are characterised by high electrical and thermal conductivities.

The data have been collected from various sources, including both published literature and information supplied privately by manufacturers. The Association wishes to thank all those who have so willingly helped in the work, and in particular to acknowledge permission to use photographs or to photograph objects kindly lent for the purpose by the following organisations:

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A list of other publications by the Copper Development Association will be found on page 54. Copies can be obtained, free of charge, on application to the Association by those giving evidence of responsible status or genuine interest. The services of the technical staff of the Association are also available, free of charge, to those who are concerned with copper or any of its applications.

E. VOCE

September, 1959

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INTRODUCTION

The four alloys covered by this booklet form a group of materials of wide application in the electrical industry and, in general, for purposes where high electrical and thermal conductivities are required. Silver, in the amounts considered in this publication, has no appreciable effect on the conductivity of copper, but the other three elements decrease it slightly. However, they impart other desirable properties, to gain which some degree of conductivity can legitimately be sacrificed. In particular, cadmium and chromium impart increased strength and resistance to wear, while tellurium improves the machinability. All four elements increase the temperature at which copper anneals and softens, and silver is used specifically for this purpose.

The fields in which these qualities can be employed to advantage are numerous and varied. To give a few examples, cadmium copper makes admirable overhead conductors of long span or trolley wire, while chromium copper, also strong and tough, is used for such items as resistance welding electrodes and cylinder heads of internal combustion engines, where its high thermal conductivity is of value. As it can be hardened by heat treatment, it is a valuable material for light electrical springs. Work-hardened silver copper does not soften at ordinary soldering temperatures; it is widely employed in the manufacture of commutators for electrical machines and in the fabrication of car radiators. An important additional advantage of silver copper is that it shows improved resistance to creep, or slow deformation at moderately elevated temperatures; it is in consequence recommended for the rotor windings of large alternators, which tend, under certain conditions, to fail by creep. Unlike ordinary copper, tellurium copper can be machined almost as easily and quickly as free-cutting brass, compared with which it has much greater conductivity. It is therefore favoured for bolts, nuts and similar machined articles destined to carry electricity, also for screwed pipe fittings for use under conditions too corrosive for brass.

The four alloys are obtainable in most of the normal wrought forms, and also, particularly in the cases of chromium copper and tellurium copper, as castings and forgings. The main output of each alloy is determined by its major applications. For instance, most cadmium copper is produced as heavy gauge wire of special sections, while silver copper is made mainly in the form of drawn sections and strip. Much chromium copper is produced as bar and also as castings and forgings, though strip and wire are available,

while the principal output of tellurium copper is in the form of round, hexagonal and square rod for automatic machines.

The quantities of the four elements in question required to confer these desirable properties on copper are quite small, the normal commercial ranges being:

Cadmium copper	0·7% to 1·0% cadmium
Chromium copper ..	0·4% to 0·8% chromium
Silver copper	0·03% to 0·1% silver
Tellurium copper	0·3% to 0·7% tellurium

Both cadmium copper and chromium copper are invariably of the deoxidised type; not only are controlled small amounts of phosphorus introduced, but cadmium and chromium also act as deoxidants. On the other hand, silver copper is generally of the tough pitch variety, containing about 0·02% to 0·05% of oxygen in the form of cuprous oxide. It is, however, obtainable in an oxygen-free grade. Tellurium copper may be either tough pitch or deoxidised as desired, the former usually possessing slightly the higher conductivity.

Chromium copper is unique among the four in requiring heat treatment to obtain the maximum strength and conductivity. It is essentially a precipitation-hardening material, the solid solubility of chromium in copper varying considerably with temperature. Though the solid solubility of cadmium in copper also varies with temperature, the effect on the properties, at least for the concentrations of cadmium met with in practice, is not great, and the possibilities of heat treatment have not been exploited. Silver copper is essentially identical with ordinary copper in structure, but tellurium copper contains particles of copper telluride as a separate phase. Like lead in turning brass, the telluride confers free-cutting qualities on the copper.

CADMIUM COPPER

Copper containing between 0·7% and 1·0% of cadmium is essentially a high conductivity material characterised by greater strength under both static and alternating stresses and better resistance to wear than ordinary copper. The improved mechanical properties are especially pronounced in the cold-worked condition, and hard drawn cadmium copper is particularly suitable for the contact wires of electric railways, tramways, trolleybuses, gantry cranes and similar equipment, and also for Post Office line wires and overhead power lines of long span. For the first-named application special sections of various shapes and sizes are available.

A second important group of applications depends on the fact that cadmium copper retains the hardness and strength imparted by cold work at temperatures well above those at which high conductivity copper would soften. Examples are electrode holders for resistance welding machines and arc furnaces, and electrodes for the spot and seam welding of steel and, to a lesser degree, of aluminium alloys. Such components are generally fabricated from wrought bar or plate by machining, bending or other forming processes. Cadmium copper has also been employed for the commutator bars of certain types of electric motors.

Because of its comparatively high elastic limit in the work-hardened condition, cadmium copper is also used to a limited extent for small springs required to carry electric current. These may be made from either strip or wire. A related application, based on the ability of cadmium copper to withstand repeated reverse bending without damage, is that of tinsel for the flexible cords of telephone instruments and switchboards. In the form of thin hard-rolled strip an important use is for reinforcing the lead sheaths of electric cables which operate under internal pressure.

Castings of cadmium copper are comparatively rarely made, though they have certain applications, notably for switchgear components and the secondaries of transformers for welding machines.

The main output of cadmium copper is in the form of wire, especially in heavy sections for contact wires and in round wires of moderate gauge for telephone open lines and stranded conductors.

Production

Cadmium copper is prepared by remelting high conductivity copper in suitable furnaces and adding the necessary cadmium in the form of a copper-cadmium master alloy, or by "side casting"

from holding furnaces fed by the large reverberatories of refineries. It is essential for the melt to be deoxidised by providing a charcoal cover and by the addition of a vigorous deoxidant such as phosphor-copper before adding the master alloy. The amount of phosphor-copper is carefully controlled in order to avoid more than about 0·01% residual phosphorus, which would lower the conductivity of the product. Molten cadmium tends to give off dangerous brown fumes, and good ventilation of the casting shops is essential.

The normal form of the casting is a wire bar some 4 ft. in length and about 4 in. × 4 in. in section. Water-cooled copper moulds are said to give more satisfactory results with cadmium copper than moulds made of iron, but the latter are not infrequently used. Being a deoxidised material, the metal contracts on solidification, and to facilitate feeding, wire bars of cadmium copper are invariably cast vertically. Moreover, flaming mould dressings can be used. In these respects the practice for cadmium copper differs from that for ordinary tough pitch high conductivity copper, which is extensively cast in horizontal moulds dressed with an aqueous suspension of bone ash.

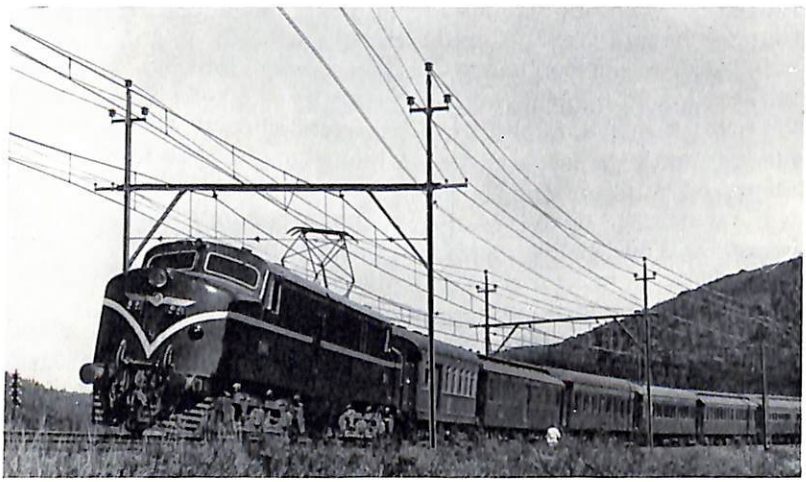
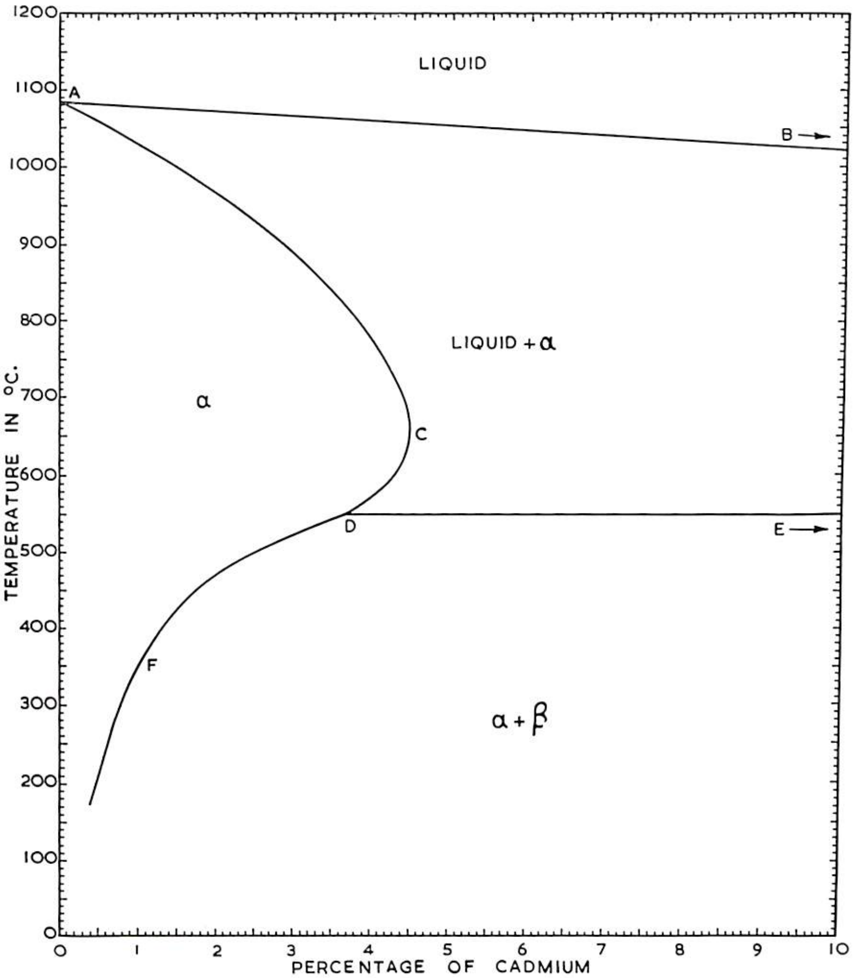


Fig. 2. Cadmium copper conductors are used on electric railways.

The cast bars are hot rolled before drawing to wire. Sometimes a pause is made in the hot rolling process, allowing the metal to cool sufficiently to acquire some degree of cold work during the



Point	A	B	C	D	E	F
°C.	1083	1020	650	549	549	350
Cd (%) ..	0	10	4·5	3·7	10	1·0

Fig. 3. Equilibrium diagram of copper-cadmium system.

(After M. Hansen, *Aufbau der Zweistofflegierungen*, 1936; E. Raub, *Metallforschung*, 1947, **2**, 119.)

process. Normal practice is followed in drawing the rod to wire, using dies of suitable shape in the case of trolley wire. The wire is almost invariably supplied in the hard drawn condition.

Limited quantities of sheet and strip are produced by rolling, and of rod by extrusion and drawing.

Structure

From the copper-rich end of the equilibrium diagram shown on page 5 it will be seen that the commercial alloy containing about 0·8% of cadmium consists of a single phase α solid solution at all temperatures between about 300° C. and the melting point. Below 300° C. there is theoretically a possibility of separation of the β phase, perhaps accompanied by precipitation hardening. The reaction is, however, sluggish, and its effect, if any, on the properties of the material is not exploited in practice.

Table I

PHYSICAL PROPERTIES OF CADMIUM COPPER

Density at 20° C.	8·94	gm./c.c.
Weight per cubic foot	558·4	lb.
Coefficient of linear expansion ..	17×10^{-6}	per °C.
Solidus (incipient melting) ..	1040	°C.
Liquidus (completely molten) ..	1080	°C.
Modulus of elasticity	18×10^{6}	lb./sq. in.
Modulus of torsion or rigidity ..	6×10^{6}	lb./sq. in.
Specific heat at 20° C.	0·092	
Thermal conductivity at 20° C.	0·9	cal./sq. cm./cm./sec./°C.
Temperature coefficient of thermal conductivity	Negligible	
Electrical conductivity at 20° C. (annealed)	90–97	% I.A.C.S.
Electrical conductivity at 20° C. (cold worked)	80–92	% I.A.C.S.
Electrical resistivity at 20° C. (annealed)	1·78–1·92	microhm cm.
Electrical resistivity at 20° C. (cold worked)	1·87–2·15	microhm cm.
Temperature coefficient of electrical resistivity at 20° C.	0·003–0·0037	per °C.
Ditto. Usual figure for hard drawn wire	0·00304	per °C.

Physical Properties

The figures given for the physical and mechanical properties for cadmium copper are considered to be representative of the material as commercially produced.

The physical properties are set out in Table I.

Tensile Properties

The properties of cadmium copper as revealed by tensile tests are indicated in Table II, in which figures for tough pitch high conductivity copper are included for comparison. Though the data in this table refer specifically to wire, they can be accepted as indicative of bar and rolled strip for similar degrees of cold work. As, however, reductions rarely exceed about 75% for such products, the full advantages achieved by heavy cold work cannot be attained. In general, the degree of reduction obtainable, and consequently the mechanical properties, depends to a considerable extent on the size of the product.

The table demonstrates the marked superiority in tensile strength of cadmium copper over ordinary high conductivity copper, a feature which is one of its principal assets.

Table II

TENSILE PROPERTIES OF CADMIUM COPPER WIRE

Condition	Cadmium Copper		Tough Pitch H.C. Copper	
	Tensile Strength (tons/sq. in.)	Elongation (% on 10 in.)	Tensile Strength (tons/sq. in.)	Elongation (% on 10 in.)
Annealed	17–20	45	14	45
Cold drawn:				
50% reduction..	27–34	2–7	24	9
75% reduction..	32–36	2–3	28	6
90% reduction..	36–40	1·5–2·0	30	5
95% reduction..	40–50	1·0–1·5	31	4

Elastic Properties

The limit of proportionality of cadmium copper in the annealed condition is about 3 tons/sq. in., and the proof stress for 0·1%

permanent extension is about 5 tons/sq. in. Small amounts of cold work cause a rapid increase in both these figures, and for this reason appreciably higher values are found for hot rolled rod, particularly in small sizes. Cold working of the annealed material to 25% reduction of sectional area increases the limit of proportionality to about 10 tons/sq. in. and the 0·1% proof stress to about 25 tons/sq. in. Severe cold working such as that applied in drawing rod from $\frac{3}{8}$ in. diameter to less than $\frac{1}{8}$ in. diameter (about 90% reduction of area) further raises the limit of proportionality to approximately 20 tons/sq. in. and the 0·1% proof stress to as much as 40 tons/sq. in., though exact figures depend on the conditions of drawing and the size of the product.

Elastic moduli for tension and torsion are included in Table I.

Hardness

Like the tensile strength, the hardness of cadmium copper is considerably greater than that of ordinary high conductivity copper, especially in the cold-worked condition. Vickers hardness values in the neighbourhood of 140 D.P.N. can be attained, whereas those of ordinary copper rarely exceed about 115 D.P.N.

Fatigue Properties

Under alternating stresses cadmium copper is, like other materials, somewhat sensitive to surface condition, and small flaws or other imperfections may appreciably reduce the fatigue resistance.

The figures given in Table III are based on work by Anderson, Swan and Palmer,* who used carefully polished specimens and who state that their results approximate to ideal endurance strengths in air, free from the influence of such disturbing factors as notches or corrosion. The material for the tests in the annealed condition contained 1·02% cadmium, while that tested in the hard drawn condition carried 1·12% cadmium. In each case comparable tests were carried out on electrolytically refined high conductivity tough pitch copper, and the marked improvement in the fatigue properties conferred by cadmium is apparent from the results. It is noteworthy that the hard drawn cadmium copper, unlike the other materials tested, appears to reach a definite fatigue limit of $\pm$ 13·4 tons/sq. in. after 30,000,000 cycles of stress. In view of the effect of surface imperfections, however, this figure may well exceed that which it is desirable to accept for practical purposes. The aim of the table

* A. R. Anderson, E. F. Swan and E. W. Palmer. *Proc. Amer. Soc. Test. Mat.*, 1946, Vol. 46, p. 678.

is to illustrate the superiority of cadmium copper over H.C. copper under strictly comparable conditions rather than to provide design data. Moreover, the cadmium content of these wires was somewhat greater than that normally used for conductors.

Table III

FATIGUE PROPERTIES OF CADMIUM COPPER IN COMPARISON WITH HIGH CONDUCTIVITY TOUGH PITCH COPPER

(Anderson, Swan and Palmer)

Millions of Reversals	Range of Alternating Stress (tons per sq. in.) for failure after stated number of reversals			
	Cadmium Copper		H.C. Copper	
	Annealed 1 hour, 650° C.	Cold drawn 29% redn.	Annealed 1¼ hours, 600° C.	Cold drawn 36% redn.
0·1	11·6	24·5	9·8	15·2
0·3	9·8	20·1	8·0	12·9
1	8·9	17·0	6·7	11·2
3	8·0	15·2	5·8	9·2
10	7·1	14·2	5·2	8·5
30	6·7	13·4	4·7	8·1
100	6·6	13·4	4·5	7·8
300	6·5	13·4	4·0	7·6
1,000	6·3	13·3	3·8	7·5
Tensile strength ..	15·7	32·6	13·9	21·8

Creep Properties

Apart from a few tests at 140° C. by Holley and Savage* on an alloy with one-fifth of the normal cadmium content, no creep data on cadmium copper have been traced. The experiments in question indicate that cadmium confers a marked improvement in the creep resistance of copper.

* C. H. Holley and R. E. Savage. *Power Apparatus and Systems*, 1955, April, No. 17, p. 72.

Shear Strength and Impact Value

The shear strength of cadmium copper varies from about 12 tons/sq. in. for annealed material upward to 25 tons/sq. in. for material in the hard condition. The Izod impact value remains between about 50 and 60 ft.-lb., irrespective of condition.

Resistance to Wear

Resistance to wear is a property which is difficult to assess or to express in a quantitative manner, but experience shows that, in such applications as contact and trolley wire, cadmium copper gives improved service over ordinary high conductivity copper. Its greater hardness is doubtless an important factor in conferring resistance to abrasion by rubbing. Moreover, the higher limit of proportionality enables cadmium copper wires to be tensioned to a greater stress while remaining resistant to creep, so that sagging of the lines is avoided. This reduces arcing, which is another prevalent cause of wear.

Softening Temperature

Cold-worked cadmium copper commences to recrystallise and soften at temperatures somewhat above 200° C., but this is high enough to enable such operations as soft soldering and the baking of electrical insulation to be carried out without appreciably reducing the mechanical properties. Moreover, cold-worked cadmium

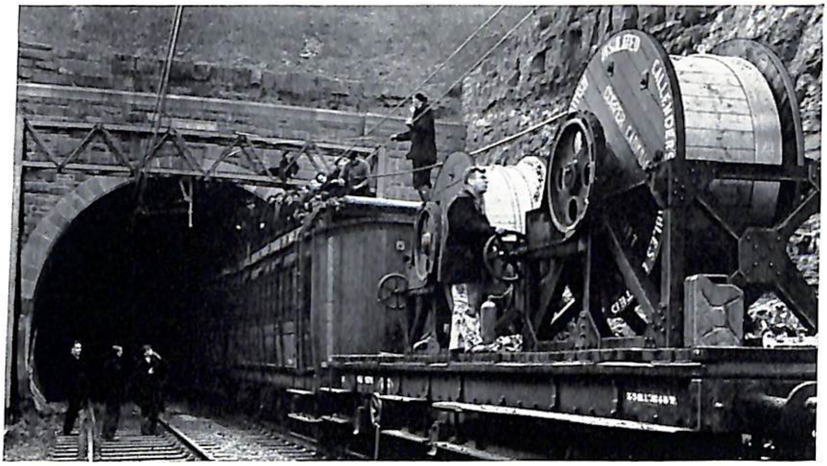


Fig. 4. Wiring Woodhead Tunnel with cadmium copper conductors.

copper can, if desired, be put into service at temperatures up to, say, 150° C. without serious risk of softening. Its use for welding electrodes and holders is an example.

Resistance to Corrosion

The corrosion resistance of cadmium copper is indistinguishable from that of ordinary copper. On exposure to the atmosphere, as for instance in the case of trolley and line wires, it acquires the normal protective patina except on rubbed surfaces, which remain bright. It is rarely required for service under more corrosive conditions.

Joining

Cadmium copper can be soft soldered, silver soldered and brazed in the same manner as ordinary copper, and, being a deoxidised material, there is no risk of embrittlement by reducing gases during such processes. In gas or arc welding, a flux containing sodium fluoride as an addition to fused borax or boric acid is recommended to dissolve cadmium oxide, should this form. For joining lengths of cadmium copper rod or wire prior to drawing to smaller sizes, resistance brazing with silver solder is preferable to butt resistance welding, which tends to give rise to porosity.

Machinability

Though cadmium copper is not a free-cutting material, it can be machined with somewhat greater ease than ordinary copper, especially in the work-hardened condition. It evinces less tendency to clog the tools, though the greater hardness may lead to slightly increased wear on the tools.

CHROMIUM COPPER

Copper containing under 1% of chromium forms a precipitation hardening alloy combining considerable strength with high electrical and thermal conductivity. As the strength arises from heat treatment rather than from cold work, it is retained at temperatures which would cause ordinary hard-worked copper to anneal and soften. Moreover, the properties are uniform throughout the metal, whereas the effects of cold work are often more intense in the surfaces actually in contact with the roll or die faces than elsewhere, particularly in the case of thick sections. Even in the fully heat-treated condition, however, chromium copper can be cold-worked to a limited extent, and by this means it is possible to enhance the strength and hardness imparted by heat treatment.

Chromium copper is available both in wrought forms, such as sheet, strip, rod, wire or forgings, and as castings.

Chromium copper is specially suitable for applications in which considerably higher strength than that of copper is required in conjunction with high electrical and thermal conductivity. Two of the chief specific applications are for welding electrodes, of both the spot and seam types, and for the cylinder heads of internal combustion engines, especially for aircraft. The cylinder heads are almost invariably machined from forgings or castings; some electrodes are made by casting, but the main output is from fabricated material. Strip and, to a lesser extent, wire are used for light springs destined to carry electric current. Chromium copper plate has been advocated for the walls of Junker type water-cooled moulds for the brass industry, and commutator segments are available for electric motors designed to operate at temperatures above those normally encountered in electrical machines.

Commercial chromium copper usually contains from about 0·4% to 0·8% chromium, a typical figure being 0·5%. Small quantities of other elements are sometimes present, especially in proprietary alloys. These generally have the effect of improving the mechanical properties at the expense of conductivity.

Production

Chromium copper is made from cathode or high conductivity ingot copper and a chromium copper master alloy. Preparation of the master alloy, which usually carries between 8% and 12% of chromium, is by no means easy, for chromium, particularly if contaminated with oxide, does not readily dissolve in molten copper.

Chromium powder for the purpose should be burnished by tumbling or ball-milling immediately before use.

Considerable care is necessary both in the manufacture of the master alloy and in its subsequent use if the evils of segregation and oxidation are to be avoided. The copper should preferably be melted under slightly oxidising conditions in order to remove dissolved hydrogen which might give rise to porosity, and deoxidised

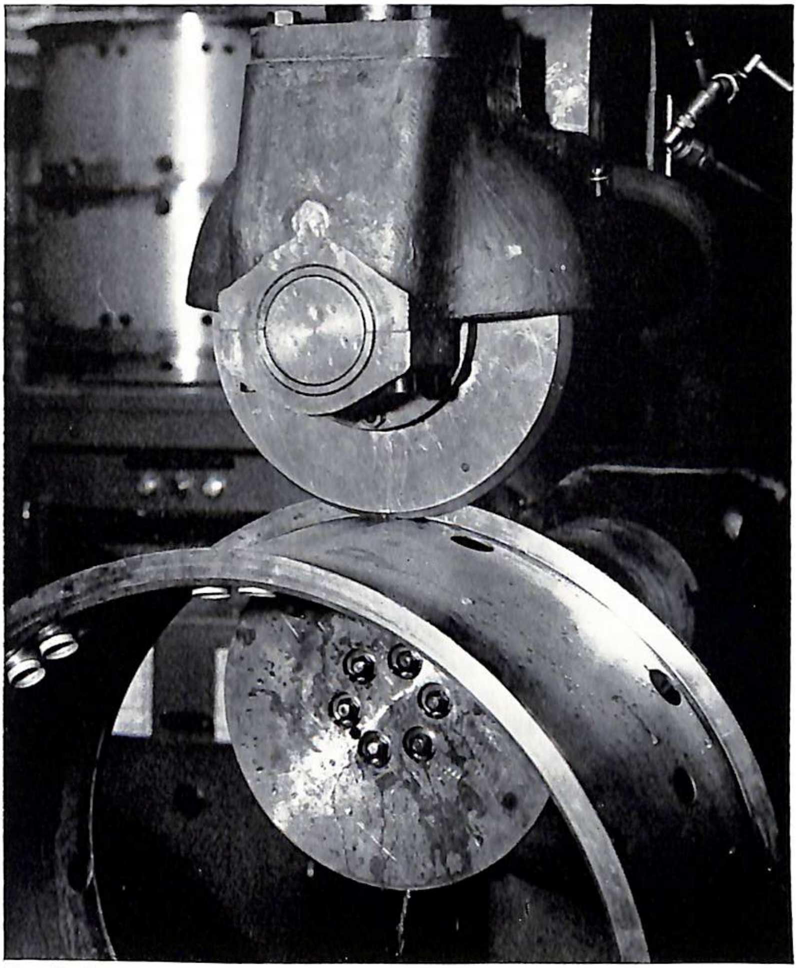


Fig. 5. Seam welding electrodes of heat-treated chromium copper in operation on an aircraft part.

with a small amount of phosphor copper or other deoxidant less detrimental to conductivity, such for instance as calcium boride.

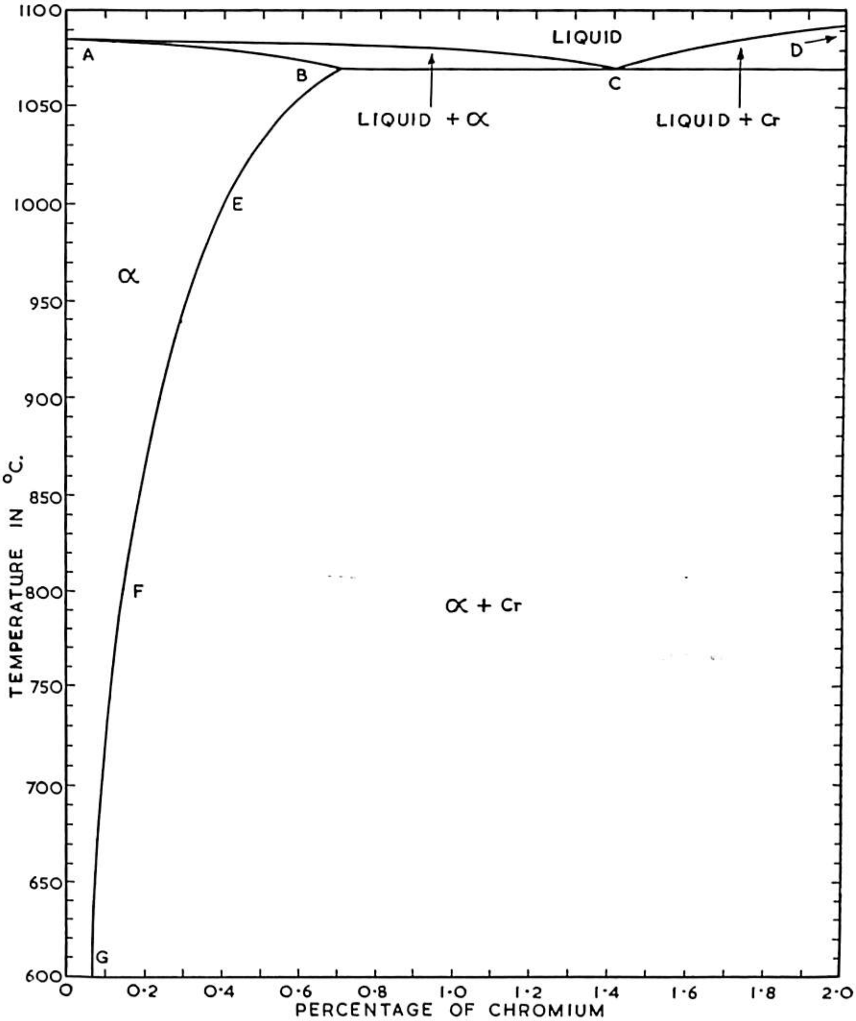
On no account should chromium or the hardener be added to an oxidised melt, lest inert chromium oxide remain entrapped in the metal. Analytical determinations of total chromium do not as a rule differentiate between the metal and its oxide, and cannot therefore be relied upon to indicate the amount of chromium present as an alloying element. Even under the best conditions, losses of chromium by oxidation may reach between 10% and 30% of the quantity charged. Stirring and skimming should be carried out with graphite tools, because contamination with iron, derived from iron tools, would be detrimental to the conductivity.

Owing to the small solidification range, shrinkage is a source of trouble in the preparation of sand castings. It is necessary to provide generous feeding heads and risers, and care should also be taken that cores are not too strong, because of the weakness of the alloy just after it has solidified. For small castings green sand practice is normally suitable, though for large castings dry sand moulds may be necessary. A permeable type of sand is desirable. When casting ingots or billets for subsequent fabrication the flaming (reducing) type of mould dressing is normally employed.

Chromium copper can be worked hot in much the same way as ordinary copper and it can also be cold rolled and drawn, especially if it has first been quenched from a temperature of 900° C. or above. Interstage annealing should also be carried out at this temperature, from which the material should be quenched in order to retain the maximum softness for further cold work. This may constitute some difficulty, for non-ferrous annealing plant is seldom designed for such high temperatures. It will be appreciated that oxidation and scaling are considerable in the temperature range mentioned, including the formation of sub-scale by the preferential oxidation of chromium beneath the surface of the alloy, and it is therefore desirable to use an inert atmosphere in the annealing furnace. Moreover, there may be considerable grain growth at the solution temperature, and to avoid these difficulties interstage annealing is sometimes carried out at temperatures between 500° and 700° C. No difficulties in the pickling of chromium copper have been reported.

Structure and Heat Treatment

The copper-rich end of the copper-chromium equilibrium diagram is given on page 15. It will be seen that the maximum solid solubility of chromium in copper is 0·7%. Commercial chromium



Point	A	B	C	D	E	F	G
°C.	1083	1070	1070	1470	1000	800	600
Cr (%) ..	0	0·7	1·4	37	0·4	0·15	0·07

Fig. 6. Equilibrium diagram of copper-chromium system.

(M. Hansen. *Aufbau der Zweistofflegierungen*, 1936.
W. R. Hibbard, F. D. Rossi, H. J. Clark and R. I. O'Herron. *Trans. Amer. Inst. Min. Met. Eng.*, 1948, **175**, 283.)

copper rarely contains more than this percentage of chromium, but if excess is present it is visible as small, scattered particles of a second phase under the microscope. If the melt has been oxidised, particles of chromium oxide will also appear in the microstructure.

The equilibrium diagram shows that the temperature range between the solid solubility limit BE and the solidus AB is very restricted for commercial materials containing about 0·5% of chromium. It extends from about 1035° to approximately 1075° C., and it is within this narrow range that solution heat treatment should ideally be performed. In practice, however, temperatures in the neighbourhood of 1000° C. or even a little lower are generally employed for the purpose. At 1000° C., for example, about 0·4% of chromium is taken into solid solution, the excess remaining as a separate phase. The heating time should be kept to a minimum in order to restrict grain growth; for thin material about 15 minutes is normally sufficient, but heavy furnace charges may require somewhat longer periods. To retain the chromium in solid solution the material must be quenched quickly, preferably in cold water. To avoid undue oxidation and scaling during the heat treatment the provision of an inert atmosphere in the furnace is recommended, or a salt bath can be used.

The solution heat treated material is comparatively soft and ductile, and can be rolled, drawn or otherwise cold worked in much the same way as ordinary copper. Only after a second or precipitation heat treatment does it assume its special properties. For this purpose the quenched material is reheated for several hours at between 400° and 500° C., 4 hours at 450° C. being typical of industrial practice. At such temperatures the solid solubility of chromium in copper is less than about 0·05%, and the excess is therefore ejected as a submicroscopic precipitate throughout the copper-rich crystals. Not only do the minute particles of chromium stiffen the crystals, but they are much less detrimental to the conductivity than chromium in solid solution. The result is a marked increase in both strength and conductivity.

The effect of progressive precipitation of chromium from solid solution on the hardness of chromium copper is shown in Tables IV and V, and on the electrical conductivity in Table VI. From Table V, based on the work of Köster and Knorr,* it is apparent that the hardness reaches a maximum of about 145 D.P.H. at all temperatures of heat treatment between 350° and 500° C. While

* W. Köster and W. Knorr. *Zeits. Metallkunde*, 1954, Vol. 45, Pt. 6, p. 350.

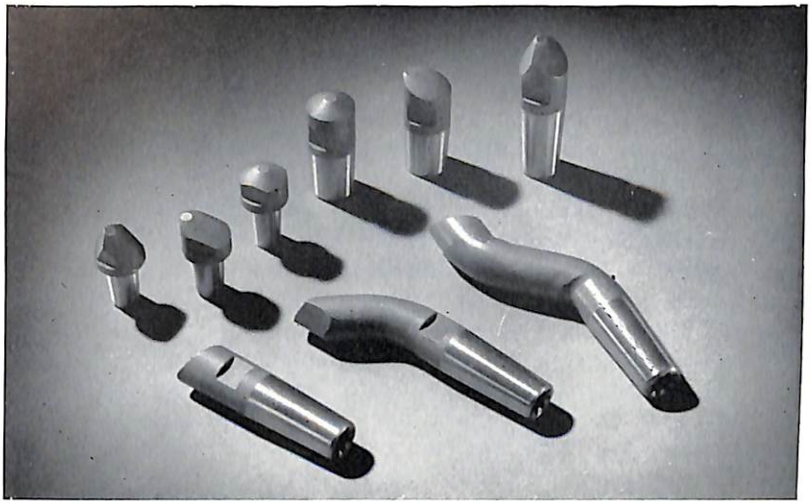


Fig. 7. Spot welding electrodes machined from heat-treated chromium copper bar.

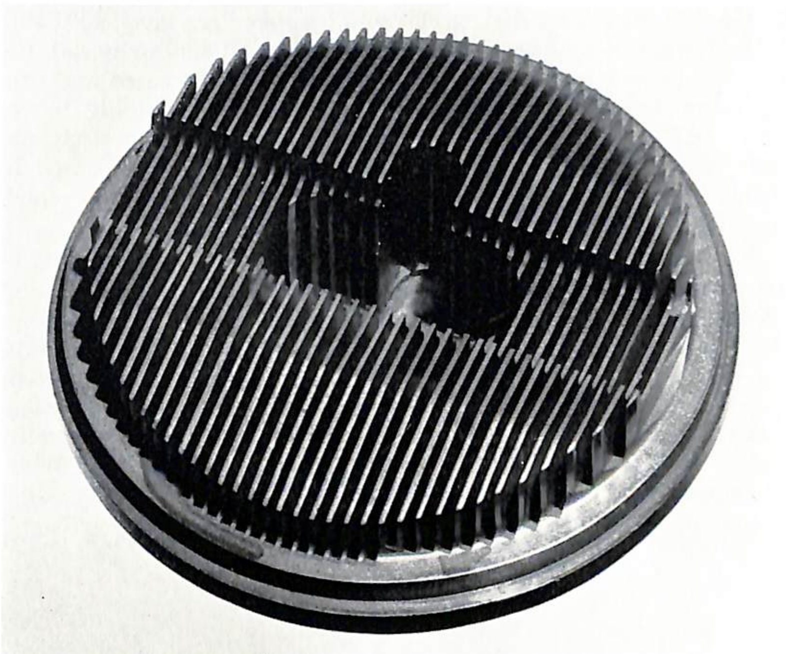


Fig. 8. Cylinder head of aircraft engine, machined from a heat-treated chromium copper forging.

the maximum is attained in less than an hour at 500° C., it requires between two and three months at 350° C. to reach the same value. The most satisfactory conditions are found in the temperature range adopted commercially, namely from 450° to 475° C. The tensile strength varies with heat treatment in substantially the same manner as the hardness.

From Table VI, also due to Köster and Knorr,* it would appear that the conductivity reaches a fixed value at each heat treatment temperature. The highest conductivities are found in the range of commercial heat treatment temperatures just mentioned, but comparison with Table V shows that the greatest conductivities are attained after longer periods of time than those required to reach the maximum hardness. A moderate degree of over-precipitation is therefore to be recommended in cases where the greatest possible conductivity is of more importance than the greatest possible hardness and strength.

Physical Properties

The physical properties of chromium copper are given in Table VII. Except in respect of electrical and thermal conductivities, the physical properties differ little in the solution heat treated and precipitation hardened conditions. The conductivities should be regarded as approximate only. They are likely to vary somewhat, not only with the exact conditions of heat treatment as indicated in Table VI, but also with the deoxidants or additional elements which may be present in proprietary alloys.

Köster and Knorr* have examined the magnetic susceptibility of chromium copper under various conditions of heat treatment, and also its thermoelectric potential against super-purity aluminium. As a knowledge of these properties is rarely called for, the results have not been reproduced here, but the reader is referred to their paper for the information in question. In connection with the magnetic susceptibility it should be noted that the material used by Köster and Knorr contained 0·015% iron in addition to 0·6% chromium.

* W. Köster and W. Knorr. *Zeits. Metallkunde*, 1954, Vol. 45, Pt. 6, p. 350.

Table IV

EFFECT OF TIME ON THE PRECIPITATION HARDENING OF COPPER CONTAINING 0·48% CHROMIUM

(Hibbard, Rossi, Clark and O'Herron. *Trans. Amer. Inst. Min. Met. Eng.*, 1948, Vol. 175, p. 283)

Duration of Precipitation Heat Treatment	Solution Heat Treated at 1050° C. for 4 hours and Quenched			
	Precipitation Hardened at 450° C. for Stated Period		Cold Rolled 25% Reduction in Thickness and Precipitation Hardened at 400° C. for Stated Period	
Hours	Rockwell F Scale	Equivalent D.P.H.	Rockwell B Scale	Equivalent D.P.H.
0	13	—	52	90
0·3	72	70	—	—
0·5	—	—	68	120
0·7	83	88	—	—
1	88	98	68	120
2	94	114	72	130
3	96	122	—	—
4	97	126	81	152
6	97	126	82	156
10	96	122	—	—
12	—	—	81	152

Table V

EFFECT OF TIME AND TEMPERATURE ON THE PRECIPITATION HARDENING OF COPPER CONTAINING 0·6% CHROMIUM WITH 0·015% IRON AFTER QUENCHING FROM 1030° C.

(Köster and Knorr. *Zeits. Metallkunde*, 1954, Vol. 45, Pt. 6, p. 350)

Period of Heat Treatment (*Hardness as quenched* 55 D.P.H.)	Diamond Pyramid Hardness after Heat Treatment for Stated Time at Stated Temperature										
	200°C.	300°C.	350°C.	400°C.	425°C.	450°C.	475° C.	500°C.	550°C.	600°C.	700°C.
2 minutes	55	55	55	56	57	—	—	—	—	112	**127**
5 minutes	—	—	56	60	61	82	102	118	125	**135**	110
10 minutes	—	—	58	63	67	93	116	123	**140**	124	99
30 minutes	—	—	59	74	87	109	124	142	132	109	78
45 minutes	—	—	—	—	—	—	—	**146**	—	—	—
1 hour	—	—	60	83	98	119	142	143	124	101	—
1½ hours	—	—	—	—	—	—	**144**	—	—	—	—
2 hours	—	57	62	93	109	130	143	137	118	93	—
5 hours	—	—	66	109	126	143	133	126	110	85	—
7 hours	—	—	—	—	—	**145**	—	—	—	—	—
10 hours	—	—	73	122	140	143	127	119	95	—	—
1 day	56	59	80	138	**147**	137	118	110	—	—	—
3 days	—	62	92	**146**	138	126	—	—	—	—	—
1 week	—	66	109	**146**	129	113	—	—	—	—	—
4 weeks	—	71	133	138	118	—	—	—	—	—	—
10 weeks	57	79	**147**	—	—	—	—	—	—	—	—

The maximum hardness reached at each temperature is printed in heavy type.

Table VI

EFFECT OF TIME AND TEMPERATURE ON THE ELECTRICAL CONDUCTIVITY OF COPPER CONTAINING 0·6% CHROMIUM WITH 0·015% IRON AFTER QUENCHING FROM 1030° C.

(Köster and Knorr. *Zeits. Metallkunde*, 1954, Vol. 45, Pt. 6, p. 350)

Period of Heat Treatment (*Conductivity as quenched* 41% I.A.C.S.)	Conductivity* per cent International Annealed Copper Standard, after Heat Treatment for Stated Period at Stated Temperature										
	200°C.	275°C.	300°C.	325°C.	350°C.	400°C.	425°C.	450°C.	475°C.	550°C.	600°C.
1 minute	—	—	—	—	—	41	45	50	53	67	78
5 minutes	—	—	—	—	—	45	53	67	71	78	81
10 minutes	41	43	43	43	43	50	60	69	74	79	83
30 minutes	41	43	43	43	45	64	69	74	81	84	84
1 hour	41	43	43	45	50	67	71	78	83	86	85
2 hours	42	43	44	46	56	69	73	79	86	88	85
5 hours	43	44	45	47	65	73	78	83	88	89	85
10 hours	43	45	47	53	67	76	81	85	89	89	85
1 day	43	47	56	64	70	78	83	87	90	89	—
3 days	43	50	61	67	75	83	88	90	93	89	—
1 week	44	54	65	71	78	86	90	91	93	—	—
4 weeks	44	60	67	—	82	—	91	91	93	—	—
2 months	45	61	70	—	84	—	92	91	93	—	—
3 months	45	—	71	—	86	—	92	92	93	—	—

* Temperature of testing not stated, but presumed to be 20° C.

Table VII

PHYSICAL PROPERTIES OF CHROMIUM COPPER

Density	8·89	gm./c.c.
Weight per cubic foot	555	lb.
Coefficient of linear expansion ..	17×10^{-6}	per °C.
Solidus (incipient melting) ..	1073	°C. (approx.)
Liquidus (completely molten) ..	1080	°C. (approx.)
Modulus of elasticity	16×10^{6}	lb./sq. in.
Modulus of rigidity or torsion ..	6×10^{6}	lb./sq. in.
Specific heat at 20° C.	0·09	
Thermal conductivity at 20° C.:		
Solution heat treated	0·4	cal./sq. cm./cm./sec./°C.
Precipitation hardened ..	0·75	cal./sq. cm./cm./sec./°C.
Electrical conductivity at 20° C.:		
Solution heat treated	45	% I.A.C.S. (approx.)
Precipitation hardened ..	82	% I.A.C.S. (approx.)
Electrical resistivity at 20° C.:		
Solution heat treated	3·83	microhm cm. (approx.)
Precipitation hardened ..	2·10	microhm cm. (approx.)
Temperature coefficient of electrical resistivity at 20° C.:		
Solution heat treated	0·002	per °C. (approx.)
Precipitation hardened ..	0·003	per °C. (approx.)

Mechanical Properties

Tensile test results for commercial chromium copper in various conditions are outlined in Table VIII. These should be regarded as a guide to the values to be expected from proprietary materials. In the solution heat treated condition the alloy retains sufficient ductility to enable considerable cold deformation to be applied. When chromium copper which has been subjected to precipitation heat treatment is cold-worked, tensile strengths in excess of 30 tons/sq. in. are obtained, and the limit of proportionality is raised to 20 tons/sq. in. Hardness values upwards of 140 D.P.H. are reached, as shown in Tables IV, V and VIII.

Gruhl and Fischer* have studied the combined effects of cold work and heat treatment on the precipitation hardening of copper containing 0·6% chromium. Their results are presented in numerous curves showing the diamond pyramid hardness as a function

* W. Gruhl and R. Fischer. *Zeits. Metallkunde*, 1955, Vol. 46, Pt. 10, p. 742.

Table VIII

MECHANICAL PROPERTIES OF CHROMIUM COPPER

	Wrought Material and Forgings		Cold Worked Material		Castings
	Solution Heat Treated	Precipitation Hardened	Precipitation Hardened and 10% Cold Reduction	Precipitation Hardened and 25% Cold Reduction	Precipitation Hardened
Tensile strength (tons/sq. in.)	15	26	30	33	22
0·1% proof stress (tons/sq. in.)	3	17	25	28	15
Limit of proportionality (tons/sq. in.)	2	14	18	20	12
Elongation on 2 in. (%) ..	50	22	15	10	15
Diamond pyramid hardness	65	130	145	150	130
Izod impact strength (ft. lb.)	—	—	—	—	65

of time at a series of temperatures for various degrees of cold deformation. At temperatures up to 275° C. the increase of hardness is slight and slow, whereas at temperatures between 300° and 600° C. a maximum is reached with increasing rapidity as the temperature is raised. Table IX gives the peak hardness and the time required to attain it for each temperature of heat treatment and each degree of cold rolling used by the authors. After passing the peak value, continued heat treatment results in a diminution of hardness, which is more pronounced for the greater degrees of cold work.

Anderson and Smith* have reported some fatigue tests on chromium copper containing 0·09% silicon in addition to 0·88% chromium. In the precipitation hardened condition, the results were:

Millions of cycles to failure	1	10	100
Alternating stress (tons/sq. in.) ..	21	17	14

* A. R. Anderson and C. S. Smith, *Proc. Amer. Soc. Test. Mat.*, 1941, Vol. 41, p. 849.

Table IX

MAXIMUM HARDNESS VALUES OBTAINED BY HEAT TREATMENT OF COPPER CONTAINING 0·6% CHROMIUM AFTER QUENCHING FROM 1030° C. FOLLOWED BY COLD ROLLING

(Gruhl and Fischer. *Zeits. Metallkunde*, 1955, Vol. 46, Pt. 10, p. 742)

Rolling Reduction (%)	0	10	30	50	70
Hardness as rolled (D.P.H.) ..	45	85	107	114	116
Heat treated at 200° C.:					
Maximum hardness (D.P.H.) ..	49	96	113	120	123
Time to reach max. (months) ..	1–3	2–3	1–3	1–3	1–3
Heat treated at 275° C.:					
Maximum hardness (D.P.H.) ..	58	109	121	124	131
Time to reach max. (months) ..	1–3	1–2	1–3	1–3	1–3
Heat treated at 350° C.:					
Maximum hardness (D.P.H.) ..	142	148	162	168	160
Time to reach max. (weeks) ..	12	12	12	12	1
Heat treated at 400° C.:					
Maximum hardness (D.P.H.) ..	140	158	159	164	158
Time to reach max. (hours) ..	30	30	30	40	20
Heat treated at 500° C.:					
Maximum hardness (D.P.H.) ..	141	149	158	167	170
Time to reach max. (minutes) ..	25	25	10	10	10
Heat treated at 600° C.:					
Maximum hardness (D.P.H.) ..	122	125	136	139	139
Time to reach max. (minutes) ..	3	3	3	$2\frac{1}{2}$	$2\frac{1}{2}$

Properties at Elevated Temperatures

Chromium copper in the heat-treated condition can be used at temperatures up to about 350° C. without risk of deterioration of properties. The following figures for material which had received the final heat treatment after cold working indicate no change in hardness after a month at 250° C. but a distinct fall after a day at 400° C.:

Heat-treated chromium copper	143 D.P.H.
After 1 month at 250° C...	144 D.P.H.
After 24 hours at 400° C.	130 D.P.H.

Ordinary tensile tests at 400° C. on cold drawn and heat treated chromium copper rod gave the following results:

Tested at 400° C.	After ½ hour at 400° C.	After 5 hours at 400° C.
Tensile strength, tons/sq. in. ..	17	17
Elongation, % on 4√area	1	2
Reduction of area, %	3	10
Notched bar impact test, ft. lb. ..	40	—

Though the elongation figures are low at 400° C., yet the impact test shows considerable toughness. The slight increase in ductility as the time of exposure is increased is consistent with the fall in hardness after a day at 400° C.

A few creep tests at 250° and 400° C. on cold drawn and heat-treated chromium copper rod are recorded in Table X. Though at

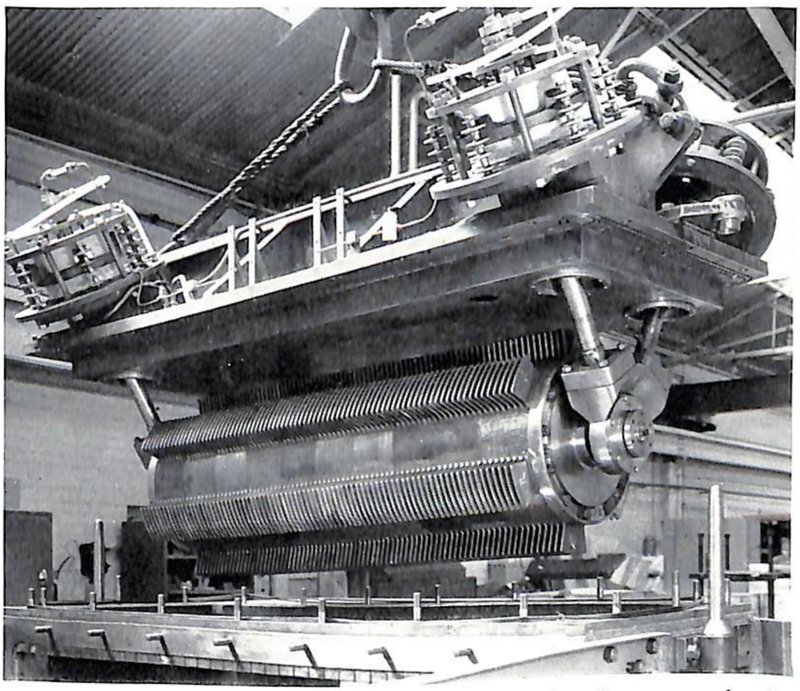


Fig. 9. Large rotor, containing $1\frac{1}{4}$ tons of heat-treated chromium copper, for the rotating condenser of a synchrotron.

Table X

CREEP TESTS ON 0·5% CHROMIUM COPPER
COLD WORKED AND PRECIPITATION HARDENED

Temperature of test, °C. ..	250	250	250	250	400
Stress, tons/sq. in.	0·7	1·4	2·8	5·6	2·5
Duration of test, days	18	43	43	43	57
Strain on loading, in./in. $\times 10^{-4}$	0·5	0·9	3·5	8·0	3·3
Total strain at end of test, in./in. $\times 10^{-4}$	1·7	2·2	12·1	63·3	19·2
Approximate minimum strain rate, in./in./day $\times 10^{-5}$	0·36	0·17	0·60	7·1	3·1

Approximate stress for a strain rate at 250° C. of

10^{-6} in./in./day	1·1 tons/sq. in.
10^{-5} in./in./day	3·3 tons/sq. in.
10^{-4} in./in./day	6·0 tons/sq. in.

low stress and not of long duration, these give some indication of the creep properties which may be expected. Users would be well advised to consult the manufacturer if the material is required for service at higher stresses and temperatures.

Machinability

In the solution heat-treated condition chromium copper is soft and can easily be machined, nor is it difficult to cut in the hardened state. Chromium copper is not, however, a free-machining material like free-machining brass or tellurium copper.

Resistance to Corrosion

Chromium copper is similar to ordinary copper in its resistance to corrosion. Like copper, it gives excellent service under all normal conditions of exposure, and can be used in chemical plant where copper itself would be permissible.

Chromium copper is also comparable with ordinary copper in respect of oxidation and scaling at elevated temperatures. The quantity of chromium present is insufficient appreciably to modify the behaviour of the alloy under such conditions.

Heat treatment has no important effect on the resistance of chromium copper to corrosive environments.

Joining

Chromium copper can be soft soldered, silver soldered and

brazed, provided that the surfaces to be joined are clean. Special fluxes are desirable to prevent the formation of the refractory oxide of chromium or to remove it if formed. Fluxes containing fluorides, with or without the addition of alkali chlorides, are generally recommended.

No reliable information on the welding of chromium copper appears to be available.

The temperature to which the material must be raised in such joining processes must be considered in the light of its precipitation hardening properties. Soft soldering must be carried out after the final heat treatment, as otherwise the joint would melt. On the other hand, silver soldering, brazing and welding should be performed before the material receives its final heat treatment, which is performed at a lower temperature than that required for such joining processes. The temperatures to which the metal must be exposed for joining may interfere with its response to heat treatment, and for this reason designers are advised to avoid brazed or welded joints in chromium copper as far as is practicable.

SILVER COPPER

Silver copper has an electrical conductivity equal to that of ordinary high conductivity copper, but in comparison with the latter possesses two properties which are of practical importance. Its softening temperature after hardening by cold work is considerably higher, and its resistance to creep at moderately elevated temperatures is enhanced. Moreover, the low-temperature heat treatment of cold worked silver copper raises the limit of proportionality considerably.

The principal uses of silver copper are in connection with electrical machines which either run at somewhat elevated temperatures or are exposed to them during manufacture, as for example where soft soldering or stoving of insulating materials has to be applied. For the same reason it is favoured for motor car radiators or other heat exchangers which have to be soft soldered, and for photogravure printing plates which require to be heated for the "burning in" of the gelatine resist. Work-hardened silver copper has been successfully adopted to combat the "shortening," which may lead to failure, of the rotor windings of alternators.

Silver copper is obtainable in the form of hard drawn or rolled rods and sections, especially those designed for commutator segments, rotor bars and similar electrical applications. It is also available as hard drawn wire, and can be fabricated into sheet and strip. It is rarely called for in the annealed condition, since its outstanding property is the retention of work-hardness at higher temperatures than silver-free high conductivity copper.

Composition and Structure

Commercial silver copper normally contains between about 0·03 and 0·1% of silver together with approximately 0·03% of oxygen as cuprous oxide. About 0·08% of silver can be accepted as the average, for the addition of more silver than this does not appreciably enhance the resistance to softening. The oxygen content brings the material into the category of "tough pitch" copper, though oxygen-free high conductivity copper containing silver is also made to a limited extent.

The structure is indistinguishable from that of ordinary high conductivity tough pitch copper, since the whole of the silver remains in solid solution in the copper.

Production

Most silver copper is prepared by the direct addition of silver or of a silver-copper master alloy to molten high conductivity copper in the refinery or cathode remelting furnace. It is rarely made in small batches by crucible melting, under which conditions it is difficult to control the oxygen content ("pitch").

Silver copper can be fabricated by hot and cold rolling, extrusion, forging, drawing and other processes in exactly the same manner as ordinary high conductivity copper. As with any other grade of tough pitch copper, it must not be annealed in atmospheres rich in hydrogen lest embrittlement by "gassing" occur.

Fig. 10. Commutators with segments of silver copper.

Physical Properties

The physical properties of silver copper can be accepted as almost identical with those of ordinary high conductivity copper. Some typical values are given in Table XI, while electrical conductivities for copper with various silver contents appear in Tables

XII and XIII. Table XII is based on work by Kenny and Craig,* who tested material with somewhat higher oxygen content than is usual in modern high conductivity tough pitch coppers. Table XIII records results by Smart and Smith† on copper of exceptionally high purity, both with and without oxygen. Both these tables show that silver, in the amounts met with in normal practice, is without appreciable effect on the conductivity, and that the oxygen content within the usual commercial limits is equally unimportant.

Benson, McKeown and Mends‡ give the figures shown in Table XIV for the effects of both temperature and cold work on the electrical conductivities of copper with and without silver, and with and without oxygen.

Table XI

PHYSICAL PROPERTIES OF SILVER COPPER

Density at 20° C.	8·89	gm./c.c.
Weight per cubic foot	555	lb.
Coefficient of linear expansion	17×10^{-6}	per °C.
Melting point	1082	°C. approx.
Modulus of elasticity	18×10^{6}	lb./sq. in.
Modulus of torsion or rigidity	6×10^{6}	lb./sq. in.
Specific heat at 20° C.	0·092	
Specific heat at 300° C.	0·098	
Thermal conductivity at 20° C.	0·93	cal./sq. cm./cm./ sec./°C.
Temperature coefficient of thermal conductivity	Negligible	
Electrical conductivity at 20° C. (annealed)	101	% I.A.C.S.
Electrical conductivity at 20° C. (cold worked)	98	% I.A.C.S.
Electrical resistivity at 20° C. (annealed)	1·705	microhm cm.
Electrical resistivity at 20° C. (cold worked)	1·76	microhm cm.
Temperature coefficient of electrical resistivity at 20° C.	0·00393	per °C.

* H. C. Kenny and G. L. Craig. *Trans. Amer. Inst. Min. Met. Eng.*, 1934, Vol. 111, p. 196.

† J. S. Smart and A. A. Smith. *Ibid.*, 1943, Vol. 152, p. 103.

‡ N. D. Benson, J. McKeown and D. N. Mends. *J. Inst. Metals*, 1951, Vol. 80, p. 131.

Table XII

EFFECT OF SILVER ON THE ELECTRICAL CONDUCTIVITY OF ANNEALED COPPER

(Kenny and Craig)

Silver (%)	Oxygen (%)	Conductivity (% I.A.C.S.)
0·001	0·053	101·0
0·023	0·059	100·8
0·035	0·068	100·5
0·052	0·060	100·6
0·069	0·048	100·7
0·086	0·048	100·6
0·103	0·067	100·2
0·122	0·068	100·1
0·132	0·056	100·1

The oxygen content of the samples was greater than is usual in most modern high conductivity tough pitch coppers, but oxygen has little effect on the conductivity.

Table XIII

EFFECT OF SILVER ON THE CONDUCTIVITY OF COPPER OF EXCEPTIONALLY HIGH PURITY

(Smart and Smith)

Silver (%)	Oxygen (%)	Conductivity (% I.A.C.S.)	
		Annealed (500° C.)	Cold Drawn (75% reduction)
Nil	Nil	102·3	100·25
0·00086	Nil	102·2	100·15
0·0017	Nil	102·1	100·15
0·0034	Nil	102·3	100·25
0·0068	Nil	102·3	100·2
0·0343	Nil	102·15	99·8
0·0343	0·026	102·05	99·65

Tensile Properties and Hardness

Table XV, taken from the work of Jackson, Hall and Schwope,* shows that the tensile properties of silver copper, both in the annealed condition and after various degrees of cold work, are almost identical with those of nominally silver-free material. While these figures refer to oxygen-free copper, very similar results are obtainable with the tough pitch variety, as shown in Table XVI due to Benson, McKeown and Mends.† These authors, however, record considerably greater elongation values than Jackson, Hall and Schwope. Diamond pyramid hardness values are included in Table XVI.

Increase of the Softening Temperature

The outstanding feature of silver copper is its increased softening temperature, and figures to illustrate this are given in Tables XVII, XVIII and XIX.

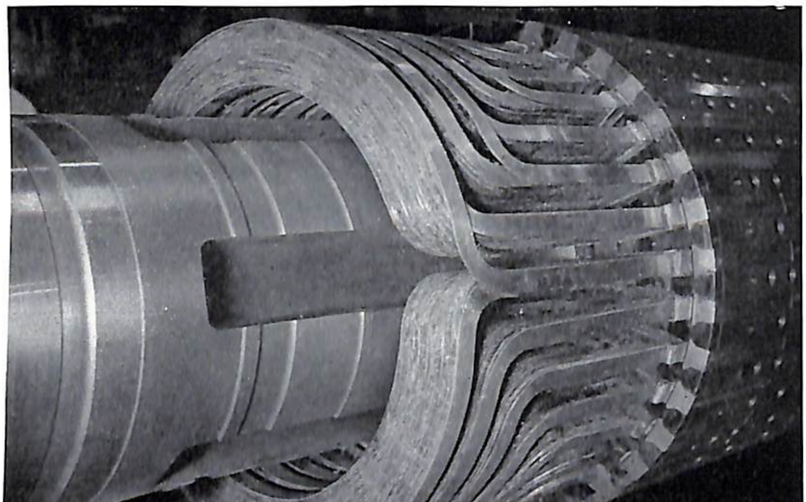


Fig. 11. Rotor of a large alternator wound with silver copper.

* L. R. Jackson, A. M. Hall and A. D. Schwope. *Trans. Amer. Inst. Min. Met. Eng.*, 1948, Vol. 175, p. 296.

† N. D. Benson, J. McKeown and D. N. Mends. *J. Inst. Metals*, 1951, Vol. 80, p. 131.

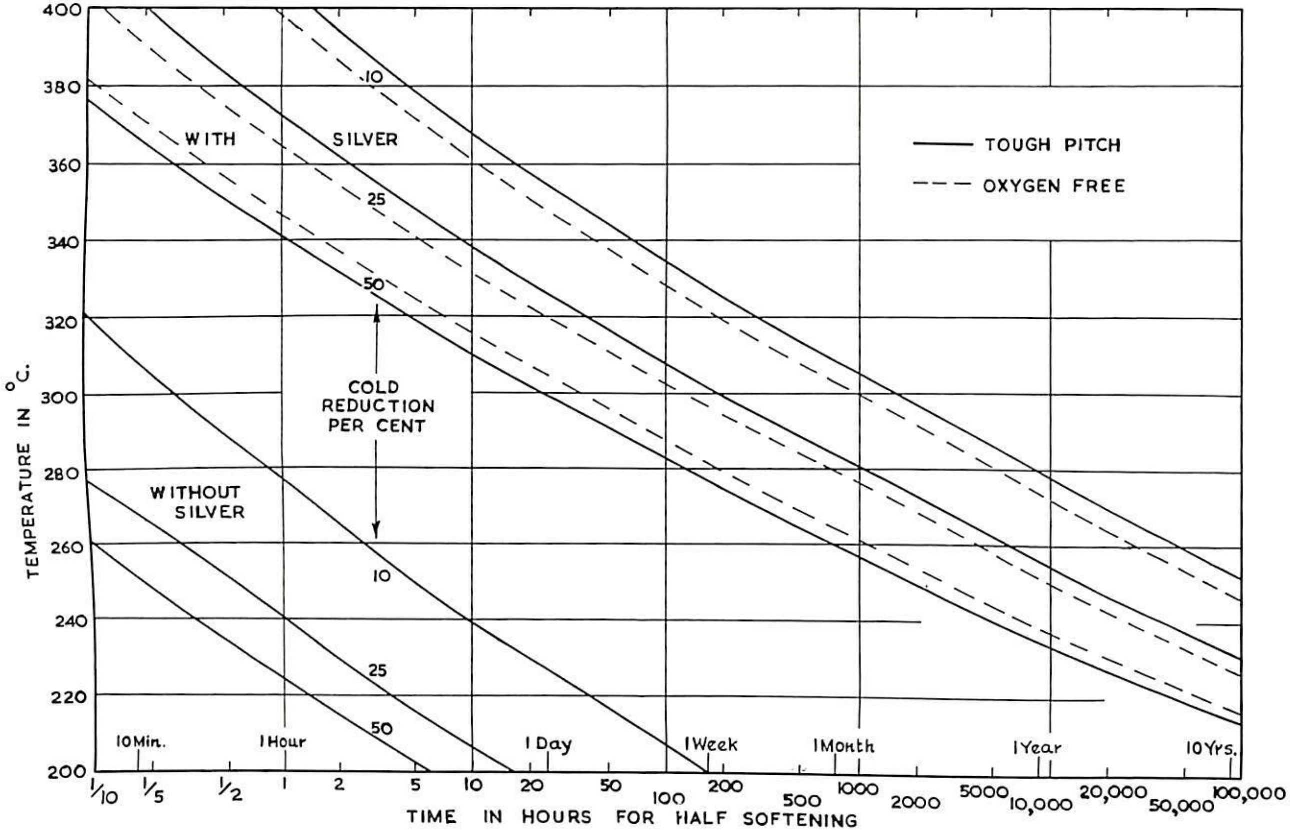


Fig. 12. Chart showing relationship between annealing temperature and time for half-softening for copper with and without silver.

Benson, McKeown and Mends studied in detail the combined effects of temperature, time, and the degree of cold work on the softening of copper with and without silver. They showed that the logarithm of the time required to soften the copper to half its initial hardness is proportional to the reciprocal of the absolute temperature. Scientifically this is an exponential relationship, but it can be expressed in the practical form

$$t = \text{antilog}_{10}\left(\frac{\alpha}{T} - \beta\right)$$

where t is the time and T the absolute temperature, while α and β are constants. When the time is expressed in hours, the constants were found to be those given in Table XX. The following example will serve to illustrate the use of the equation.

EXAMPLE: *Compare the times for half softening at* 250° *C. of high conductivity tough pitch copper with and without* 0·086% *silver, after* 25% *reduction of sectional area by cold work.*

WITH SILVER

$$t = \text{antilog}\left(\frac{11{,}500}{250 + 273} - 17{\cdot}81\right) = \text{antilog}\ (21{\cdot}99 - 17{\cdot}81)$$

$$= \text{antilog}\ 4{\cdot}18 = 1{\cdot}51 \times 10^4 \text{ hours} = 1{\cdot}7 \text{ years}$$

WITHOUT SILVER

$$t = \text{antilog}\left(\frac{7{,}500}{250 + 273} - 14{\cdot}62\right) = \text{antilog}\ (14{\cdot}33 - 14{\cdot}62)$$

$$= \text{antilog}(-0{\cdot}29) = \text{antilog}\ \bar{1}{\cdot}71 = 0{\cdot}513 \text{ hours} = 31 \text{ minutes}$$

The equation can also be used to determine the maximum temperature to which silver copper can be exposed without risk of appreciable softening in a stated period. For this purpose it must be arranged in the converse form, namely

$$T = \frac{\alpha}{\log_{10} t + \beta}$$

EXAMPLE: *To what temperature can oxygen-free silver copper cold worked to* 50% *reduction be exposed in order that it may require* 10 *years to soften to half its initial hardness?*

$$t = 10 \text{ years} = 87{,}700 \text{ hours};\ \log_{10} t = 4{\cdot}94$$

$$T = \frac{11{,}500}{4{\cdot}94 + 18{\cdot}73} = 487^\circ \text{ K.} = 214^\circ \text{ C.}$$

Table XIV

EFFECT OF TEMPERATURE AND COLD WORK ON THE ELECTRICAL CONDUCTIVITY OF COPPER WITH AND WITHOUT SILVER

(Benson, McKeown and Mends)

Composition		Cold Reduction (%)	Conductivity (% I.A.C.S. at stated temperature)		
Silver (%)	Oxygen (%)		20° C.	130° C.	170° C.
0·002	0·03	0	102·3	70·6	63·7
		10	100·8	69·8	—
		25	100·3	69·2	—
		50	99·7	69·4	—
0·086	0·02	0	101·9	70·5	63·5
		10	100·5	69·8	63·3
		25	100·4	69·8	63·1
		50	99·5	69·6	62·9
0·001	0·0002	0	102·3	70·9	63·9
		10	101·5	70·4	62·2
		25	100·1	71·1	64·5
		50	100·5	70·1	63·1
0·072	0·0003	0	102·0	71·0	63·9
		10	101·6	70·7	63·6
		25	101·1	70·3	63·2
		50	97·8	69·0	62·4

Table XV

THE MECHANICAL PROPERTIES OF OXYGEN-FREE HIGH CONDUCTIVITY COPPER WITH AND WITHOUT SILVER

(Jackson, Hall and Schwope)

Form	Silver (%)	Percentage Reduction by Cold Drawing	Proof Stress for 0·2% Extension (tons/sq. in.)	Tensile Strength (tons/sq. in.)	Elongation (% on 10 in.)	Reduction of Area (%)
0·257 in. square rod	0·0011	Annealed	3·1	14·2	38	89
		8·5	13·1	15·4	30	88
		20·5	19·7	20·1	4·5	85·5
	0·0537	Annealed	3·2	14·6	41·5	90
		8·5	13·3	15·7	31	86
		20·5	20·4	20·6	3·5	87
0·081 in. diameter wire	0·0011	Annealed	2·9	16·5	40	96
		37·1	25·4	25·7	2	91
		84·4	29·5	29·6	1·5	91
	0·0537	Annealed	4·0	16·1	40	95·5
		37·1	25·6	25·7	2	91
		84·4	29·3	29·4	1·5	91

Table XVI

EFFECT OF COLD WORK ON THE MECHANICAL PROPERTIES OF COPPER WITH AND WITHOUT SILVER

(Benson, McKeown and Mends)

Silver (%)	Oxygen (%)	Cold Reduction (%)	0·1% Proof Stress (tons/ sq. in.)	Tensile Strength (tons/ sq. in.)	Elongation %	Diamond Pyramid Hardness
0·002	0·03	0	2·3	13·8	68	48
		10	13·3	16·3	41	94
		25	17·3	20·2	19	105
		50	20·5	23·4	14	115
0·086	0·02	0	3·0	14·5	65	45
		10	13·7	16·0	46	96
		25	17·5	20·1	19	105
		50	21·3	23·8	13	116
0·001	0·0002	0	3·0	14·4	72	37
		10	13·5	15·7	44	91
		25	17·4	19·7	23	101
		50	21·2	23·8	12	111
0·072	0·0003	0	2·8	14·1	72	38
		10	13·5	15·6	52	93
		25	16·8	20·0	15	102
		50	21·1	23·3	12	115

Table XVII

EFFECT OF SILVER ON THE SOFTENING TEMPERATURE OF COPPER WIRE OF EXCEPTIONALLY HIGH PURITY COLD DRAWN TO 75% REDUCTION OF AREA (Smart and Smith)

Silver (%)	Oxygen (%)	Softening Temperature (°C.)
Nil	Nil	140
0·00086	Nil	151
0·0017	Nil	148
0·0034	Nil	155
0·0068	Nil	186
0·0343	Nil	301
0·0343	0·026	295

The softening temperature is here defined as the temperature at which the excess tensile strength imparted to the annealed material by cold work is reduced to half its value in 1 hour.

Fig. 13. The plate, in silver copper, from which Fig. 1 was printed.

Table XVIII

EFFECT OF HEAT TREATMENT ON SILVER COPPER WIRE COLD DRAWN TO 98% REDUCTION OF AREA

(Kenny and Craig)

Silver (%)	Oxygen (%)	At 150° C.		At 200° C.	
		Time (weeks)	Tensile Strength (tons/ sq. in.)	Time (weeks)	Tensile Strength (tons/ sq. in.)
0·001	0·053	0	30	0	30
		1	16	1	15
0·023	0·059	0	31	0	31
		1	29	1	21
		10	27	10	18
		30	25	20	17
0·052	0·060	0	32	0	32
		1	30	1	27
		10	29	10	24
		50	29	20	19
0·086	0·048	0	32	0	32
		1	30	1	29
		10	30	10	27
		50	29	20	26
0·103	0·067	0	33	0	33
		1	32	1	29
		10	31	10	27
		50	30	20	27

Table XIX

EFFECT OF DIPPING COLD-WORKED SILVER COPPER FOR 10 SECONDS IN A 60 : 40 LEAD-TIN BATH AT 360° C.

(Kenny and Craig)

Reduction of Area by Cold Rolling (%)	Silver (%)	Before Dipping		After Dipping	
		Tensile Strength (tons/ sq. in.)	Elongation (% on 2 in.)	Tensile Strength (tons/ sq. in.)	Elongation (% on 2 in.)
20	0·018	18·3	14	17·7	14
	0·052	17·9	17	17·9	17
	0·087	18·2	13	17·9	15
	0·119	18·0	15	18·1	14
37	0·018	22·0	2·5	19·9	7·0
	0·052	22·1	2·9	21·5	4·5
	0·087	22·5	2·8	22·0	3·3
	0·119	22·8	2·4	22·0	4·4
50	0·018	24·6	1·6	15·3	33·4
	0·052	24·3	1·6	22·9	3·2
	0·087	24·8	1·6	23·5	2·3
	0·119	25·0	1·6	23·8	2·4

It must be emphasised that the constants in Table XX were found by testing a few particular samples. While they give a useful indication of the probable behaviour of other similar materials, they should not be expected to afford high accuracy. Interpolated values of β for other degrees of cold work may be used with caution. In general, the time for incipient softening is not very much less than the time for half-softening afforded by these figures, except in the case of OFHC copper without silver, which softens more gradually than the other compositions investigated. Some values computed from the constants in Table XX are plotted in Fig. 12 on page 33, from which the times for half-softening can be read off for temperatures encountered in normal practice.

Table XX

THE SOFTENING OF COPPER WITH AND WITHOUT SILVER

(Benson, McKeown and Mends)

The approximate time in hours, t, required to reduce the hardness to half its initial value at a temperature T on the absolute scale is given by

$$t = \text{antilog}_{10}\left(\frac{\alpha}{T} - \beta\right)$$

where the constants α and β have the numerical values given below.

Silver (%)	Oxygen (%)	Cold Reduction (%)	α	β
0·002	0·03	10	7,500	13·62
		25	7,500	14·62
		50	7,500	15·06
0·086	0·02	10	11,500	16·92
		25	11,500	17·81
		50	11,500	18·73
0·001	0·0002	10	14,800	24·05
		25	14,800	25·08
		50	14,800	26·50
0·072	0·0003	10	11,500	17·15
		25	11,500	18·03
		50	11,500	18·57

Increase in the Limit of Proportionality by Heat Treatment

Hudson and McKeown* have shown that when lightly cold worked silver copper is subjected to a low-temperature heat treatment there is a distinct improvement in the limit of proportionality without appreciable alteration of the other mechanical properties. Some of the results obtained for tough pitch copper containing 0·098% silver with 0·045% oxygen cold worked to 10% reduction in area are given in Table XXI. No comparable increase in the limit of proportionality was found in the case of high-purity silver-free tough pitch copper after similar heat treatment.

Table XXI

EFFECT OF HEAT TREATMENT ON LIGHTLY COLD-WORKED COPPER CONTAINING SILVER

(Hudson and McKeown)

Composition: Copper 99·81%, silver 0·098%, oxygen 0·045%.
Cold Work: 10% reduction of area.

Treatment	Limit of Proportionality (tons/ sq. in.)	Tensile Strength (tons/ sq. in.)	Elongation (% on $4\sqrt{\overline{\text{area}}}$)
None	1·2	15·4	52
2 hours at 200° C.	2·0	15·5	51
5 hours at 200° C.	2·2	15·7	48
20 hours at 200° C.	2·8	15·6	45
2 hours at 300° C.	3·4	15·3	51
2 hours at 490° C.	Nil	14·2	66

Creep Properties

The resistance of silver copper to creep at moderately elevated temperatures is considerably better than that of ordinary high conductivity copper, especially when the material is in the cold-worked

* O. F. Hudson and J. McKeown. *J. Inst. Metals*, 1932, Vol. 48, p. 69; 1937, Vol. 60, p. 109.

condition. The improved retention of work-hardness at raised temperatures is clearly an important factor in connection with creep, but the addition of silver to copper appears to be intrinsically beneficial. This fact is brought out by the comparative figures in Table XXII for the creep at 20° C. of high conductivity copper with and without 0·02% of silver. As both materials were in the fully annealed condition, the improvement attributable to this small amount of silver is revealed independently of its effect on the softening temperature.

Table XXII

CREEP OF ANNEALED ELECTROLYTIC TOUGH PITCH AND SILVER-BEARING COPPER AT 20° C.

(Burghoff—private communication)

Silver (%)	Applied Stress (lb./sq. in.)	Initial Extension (%)	Creep Rate at 1,000 hours (% per 1,000 hours)
Nil	25,000	7·0	0·160
0·02	25,000	3·9	0·065
Nil	30,000	15·1	0·810
0·02	30,000	8·6	0·140

An extensive series of experiments on the creep of high conductivity copper, with and without silver, has been carried out by Benson, McKeown and Mends.* A synopsis of their results, supplemented by readings taken from unpublished graphs, is presented in Table XXIII. It is apparent from that table that, under comparable conditions of temperature, stress and initial cold work, the addition of silver invariably causes a diminution of the strain on loading and a marked decrease in the degree of deformation as the test proceeds. Moreover, in the absence of silver heavily cold-worked material anneals and consequently creeps rapidly at temperatures as low as 130° C. under relatively low loads. Even at the highest temperature used, namely 225° C., this tendency is not discernible in the materials containing silver.

* N. D. Benson, J. McKeown and D. N. Mends. *J. Inst. Metals*, 1951, Vol. 80, p. 131.

Table

SYNOPSIS OF CREEP TESTS ON HIGH CONDUCTIVITY COP

Temperature of Test (°C.)	Stress (lb./sq. in.)	Cold Reduction (%)	Plastic Strain (%)			
			On Loading	At 1,000 hours	At 5,000 hours	At end of Test
			TOUGH PITCH WITHOUT SILVER			
130	8,000	10	0·01	0·06	0·10	0·13
	8,000	25	0·01	0·08	0·13	0·16
	8,000	50	0·01	0·07	0·42	1·36
	14,000	10	0·02	0·16	0·36	0·51
	14,000	25	0·03	0·18	0·40	0·82
	14,000	50	0·03	0·13	1·51	6·44
	20,000	10	0·07	0·64	—	2·40*
	20,000	25	0·08	0·46	—	3·30*
	20,000	50	0·05	0·29	—	11·0*
175	8,000	10	0·01	0·16	0·62	0·96
	8,000	25	0·1	2·93	—	2·96
	8,000	50	0·5	4·3	—	4·6
	14,000	10	0·03	1·12	—	2·1*
	14,000	25	0·1	—	—	14·6*
	14,000	50	1·0	—	—	31·4*
	20,000	10	—	—	—	—
	20,000	25	—	—	—	—
	20,000	50	—	—	—	—
225	8,000	10	—	—	—	—
	8,000	25	—	—	—	—
	8,000	50	—	—	—	—
	14,000	10	—	—	—	—
	14,000	25	—	—	—	—
	14,000	50	—	—	—	—
	20,000	10	—	—	—	—
	20,000	25	—	—	—	—
	20,000	50	—	—	—	—
			OXYGEN-FREE WITHOUT SILVER			
130	14,000	25	0·02	0·07	—	0·08
	20,000	10	—	—	—	—
	20,000	25	0·03	0·15	—	0·17
	20,000	50	—	—	—	—
225	8,000	25	0·027	0·17	—	0·22
	14,000	10	—	—	—	—
	14,000	25	0·063	0·065	—	1·49
	14,000	50	—	—	—	—
	20,000	25	0·15	—	—	2·4*

XXIII

PER WITH AND WITHOUT SILVER (Benson, McKeown and Mends)

Duration of Test (hours)	Plastic Strain (%)				Duration of Test (hours)
	On Loading	At 1,000 hours	At 5,000 hours	At end of Test	
	Tough Pitch with 0·086% Silver				
8,250	0·005	0·02	—	0·03	4,750
7,200	0·005	0·02	—	0·02	4,750
8,250	0·005	0·03	—	0·03	4,550
8,600	0·015	0·04	0·06	0·08	9,800
8,600	0·015	0·05	0·07	0·07	10,200
8,700	0·015	0·06	0·08	0·09	11,400
1,750*	0·05	0·12	0·15	0·17	7,200
4,680*	0·04	0·09	0·11	0·12	7,200
4,030*	0·035	0·10	0·13	0·13	7,250
6,850	0·01	0·04	—	0·06	4,850
1,050	0·005	0·04	—	0·05	4,900
1,100	0·015	0·04	0·06	0·07	6,900
1,100*	0·015	0·09	0·12	0·16	12,900
365*	0·02	0·08	0·10	0·13	12,900
336*	0·02	0·09	0·14	0·16	12,900
—	0·11	0·24	—	0·38	4,900
—	0·04	0·14	0·21	0·26	10,300
—	0·065	0·17	—	0·22	3,700
—	0·02	0·09	0·15	0·18	8,900
—	0·02	0·07	0·11	0·13	8,900
—	0·01	0·09	0·14	0·18	8,900
—	0·06	0·20	0·39	0·68	12,900
—	0·055	0·16	0·27	0·47	11,500
—	0·03	0·20	0·34	0·62	12,900
—	0·25	—	—	1·25	760
—	0·08	0·35	0·76	1·5*	9,870
—	0·07	0·42	—	1·0	3,000
	Oxygen-free with 0·072% Silver				
1,550	0·01	0·06	—	0·06	1,550
—	0·04	—	—	0·09	750
1,550	0·02	0·09	—	0·09	1,050
—	0·01	—	—	0·09	750
2,300	0·02	0·08	—	0·11	3,150
—	0·04	0·16	—	0·16	1,050
2,750	0·05	0·21	—	0·31	3,100
—	0·03	0·14	—	0·19	3,280
275*	0·08	0·61	2·43	2·43	5,000

* Specimen broken.

Joining

Silver copper can be soft soldered, silver soldered, brazed or welded without difficulty, but the temperatures involved in all these processes, except soft soldering, are sufficient to anneal the material if in the cold-worked condition. It is, however, a primary feature of the alloy that it can be soft-soldered in the work-hardened condition without risk of softening. The effect of dipping in molten solder at 360° C. is illustrated in Table XIX.

As silver copper is usually of the "tough pitch" type, containing dispersed particles of cuprous oxide, it is important to avoid heating to brazing and welding temperatures in a reducing atmosphere. In the absence of such precautions a form of embrittlement known as "gassing," due to the interaction of hot hydrogen and cuprous oxide, may occur.

Machinability

While silver copper, like other substantially pure copper, cannot be regarded as a free-cutting material, it is not difficult to machine, especially in the work-hardened condition in which it is usually supplied.

Resistance to Corrosion

Silver copper is similar to ordinary copper in its good general resistance to corrosion. If, however, corrosive fluxes, such as those based on zinc chloride, are used for soldering, the residues should be carefully washed away before the article is put into service.

TELLURIUM COPPER

The special features of tellurium copper are ease of machining combined with high electrical conductivity, retention of work hardness at moderately elevated temperatures, and good resistance to corrosion. Tellurium copper is unsatisfactory for welding.

Tellurium copper may be used in all cases where speed and precision of machining is necessary in the production of articles the electrical or thermal conductivity of which must remain high. A classical example is the production of magnetron bodies, which in many cases are machined from solid blocks of high conductivity copper. The cutting of a complicated arrangement of slots and holes of high dimensional accuracy is greatly facilitated by the adoption of tellurium copper.

Tellurium copper has been used with advantage to replace free-cutting brass for screwed pipe unions and similar machined fittings for service in corrosive environments. Tellurium copper is not subject to the penetrative type of corrosion known as dezincification which sometimes attacks brass.

Tellurium copper is obtainable in most of the normal wrought forms and as castings. It is chiefly supplied as rod for automatic lathes and similar machines.

Composition and Structure

Commercial tellurium copper generally contains 0·3% to 0·7% of tellurium, the balance being copper. Both deoxidised and tough pitch tellurium copper are available. The latter contains approximately 0·03% of oxygen.

The structure consists of a matrix of substantially pure copper in which are embedded particles of copper telluride, as shown in the accompanying photomicrograph. These particles assist in breaking up the chips formed by cutting tools, and thus improve the machinability. In tough pitch tellurium copper particles of cuprous oxide are also present, frequently associated with the copper telluride. A small amount of tellurium remains invisibly in solid solution in the copper and tends, like silver, to raise the temperature at which cold-worked material can be softened by annealing. The proportion of tellurium which can be retained in solid solution increases somewhat as the temperature is raised, and its effect on the softening temperature is therefore greatest when the material has been quenched from a comparatively high temperature before cold working. This, however, is not recommended, since it may

lead to embrittlement if the telluride is precipitated at the grain boundaries.

For applications where a high softening temperature combined with ease of machining is of particular importance, it is possible to obtain grades of tellurium copper to which silver has been added.

Production

Copper telluride is a stable compound and is readily formed from copper and tellurium. A master alloy can be produced by heating together equal weights of copper swarf and tellurium powder at approximately 900° C. while stirring with a graphite rod. Tellurium copper can be made either by the use of an appropriate quantity of such master alloy or by the direct addition of tellurium to molten copper.

For highest conductivity the product is preferably tough pitch, the "pitch" or oxygen content being controlled by "poling" as for ordinary high conductivity copper. Mould dressings must be of the non-reducing type, such as bone ash.

In crucible melting it is by no means easy to control the oxygen

Fig. 14. Photomicrograph of tellurium copper rod in longitudinal section, showing distribution of copper telluride. Unetched. (× 100)

content, and for many purposes it is satisfactory to deoxidise the melt. Zinc, phosphorus or one of the newer deoxidants such as calcium boride, which are less detrimental to the conductivity, may be used. Deoxidised melts may be poured into moulds with oily or reducing dressings.

Under carefully controlled conditions oxygen-free tellurium copper can be produced from cathode copper with little or no deoxidant.

Tellurium copper, whether tough pitch or deoxidised, can be hot worked by such processes as hot rolling, extrusion, forging and hot stamping.

In cold working procedure it seems preferable not to reduce the sectional area by more than about 40% without annealing, though cases of much heavier reductions have been reported. With these reservations, tellurium copper can be cold rolled and drawn without difficulty.

Inter-stage annealing may be carried out at about 600–650° C. Like ordinary tough pitch copper, tough pitch tellurium copper must not be annealed in a strongly reducing atmosphere, or serious embrittlement will occur.

Physical Properties

The principal physical properties of annealed tough pitch tellurium copper appear in Table XXIV. The chief feature of the table is the high electrical conductivity, which is almost equal to

Table XXIV

PHYSICAL PROPERTIES OF TELLURIUM COPPER

Density	8·93	gm./c.c.
Weight per cubic foot	557	lb.
Coefficient of linear expansion..	18×10^{-6}	per °C.
Solidus (incipient melting) ..	1053	°C. (approx.)
Liquidus (completely molten) ..	1075	°C. (approx.)
Modulus of elasticity	17×10^{6}	lb./sq. in.
Modulus of rigidity or torsion ..	6×10^{6}	lb./sq. in. (approx.)
Specific heat at 20° C.	0·09	
Thermal conductivity at 20° C.	0·85	cal./sq. cm./cm./sec./°C.
Electrical conductivity at 20° C.	94–98	% I.A.C.S.
Electrical resistivity at 20° C. ..	1·76–1·81	microhm cm.
Temperature coefficient of electrical resistivity at 20° C.	0·0037	per °C. (approx.)

that of pure copper. The figures refer to the tough pitch grade of material; the thermal and electrical conductivities of the deoxidised variety will be somewhat lower than the values recorded in the table, depending on the nature and quantity of the deoxidant present.

Mechanical Properties

Typical mechanical properties of tellurium copper are given in Table XXV for material in several different conditions. In general the mechanical properties are similar to those of ordinary high conductivity copper. The Izod impact values are, however, appreciably diminished by the presence of the tellurium, and, without being brittle, tellurium copper is consequently somewhat less tough under shock loading than ordinary copper.

Table XXV

MECHANICAL PROPERTIES OF TELLURIUM COPPER

	Hot Worked (extruded or forged)	Cold Worked and Annealed	Cold Worked to about 25% Reduction in Area
Proof stress for 0·1% extension (tons/sq. in.)	3	2·5	17
Tensile strength (tons/sq. in.) ..	16	15	20
Elongation on $4\sqrt{\text{area}}$ (%) ..	45	50	12
Reduction in area (%)	40	40	20
Diamond pyramid hardness ..	50	50	100
Izod impact value (ft. lb.) ..	30	—	10
Shear stress (tons/sq. in.) ..	—	—	12
Fatigue strength* (tons/sq. in.) ..	5·5	—	7

* For about 10 million reversals of stress.

Machinability

The machinability of tellurium copper can best be summed up in the statement that its behaviour in all normal operations is closely similar to that of free-cutting brass. The overall cost of machining a given part in tellurium copper, including the important

factor of tool wear, is very much less than in ordinary copper of equal electrical conductivity, and the resultant surface is much superior. The same tool angles, speeds and feeds should be used as for free-cutting brass, with a liberal supply of cutting fluid. Fuller information is given in C.D.A. Publication No. 34, *The Machining of Copper and its Alloys.*

Retention of Work-hardness at Elevated Temperatures

The effect of tellurium in raising the softening temperature is due to the small proportion of this element which remains in solid solution in the copper, and not to that which occurs as discrete particles of copper telluride. To obtain the maximum increase in softening temperature the material should be quenched from about 800° C. prior to the cold working operations the work-hardening of which it is desired to retain. This practice tends slightly to reduce the electrical conductivity and may lead to embrittlement by precipitation of telluride at the grain boundaries. For such reasons it is seldom used commercially. When work-hardened to between 90 and 100 Diamond Pyramid Numbers and heated at

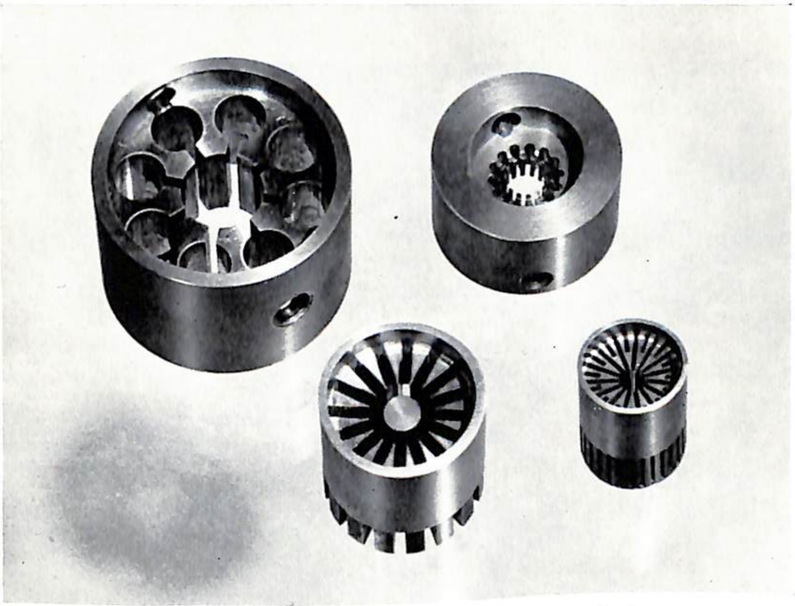


Fig. 15. Magnetron bodies and coolers machined from tellurium copper.

350° C., ordinary high conductivity copper is almost completely softened in 10 minutes, whereas the softening of tellurium copper is scarcely perceptible after two hours.

Resistance to Corrosion

The presence of tellurium in commercial amounts has little effect on the resistance of copper to corrosion, but in many environments copper is superior to brass, and tellurium copper is equally superior to free-machining brass. Advantage can be taken of this fact in the production of machined parts, such as screwed pipe fittings, for service under corrosive conditions, for example in the handling of mine waters.

Joining

Tellurium copper can be soft soldered, silver soldered and brazed without difficulty, but is unsatisfactory for welding, because bubbling of the molten tellurium copper leads to porosity and weakness of the joint.

In the case of tough pitch tellurium copper, which contains particles of cuprous oxide, brazing should be carried out in an inert

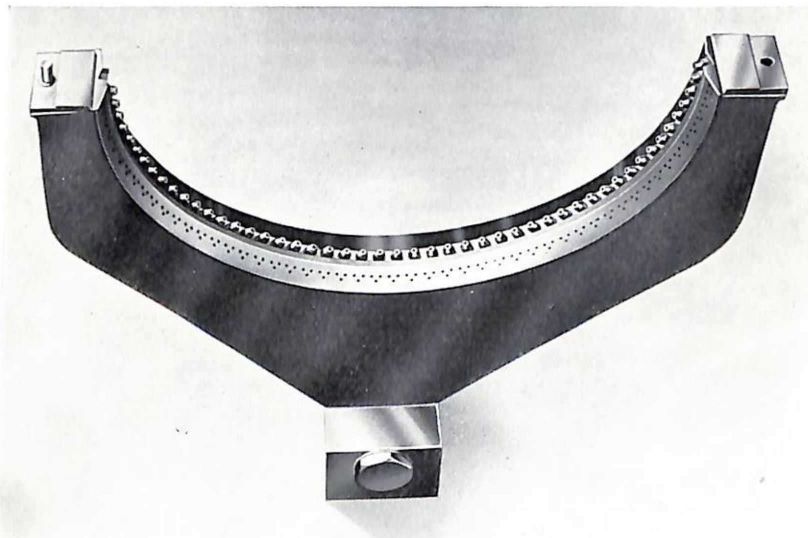


Fig. 16. Gas burner machined from tellurium copper.

or slightly oxidising atmosphere, since reducing atmospheres are conducive to embrittlement by "gassing" at the temperatures concerned. Deoxidised tellurium copper is not subject to embrittlement under such conditions.

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26. *Copper and Brass Pressings.* An illustrated book describing the principal processes employed in the manufacture of copper, brass, nickel silver and other copper alloy strip and sheet products, including blanking, deep drawing and spinning. Contains details of properties, composition and commercial tolerances of sheet, strip and foil (82 pp.).

29. *Copper in Cast Steel and Iron.* A metallurgical account of the influence of copper on the manufacture and properties of iron and steel castings, with numerous diagrams and tables (132 pp.).

31. *Aluminium Bronze.* A comprehensive account of the copper-aluminium alloys, their properties, production and applications; with numerous illustrations, diagrams and tables (168 pp.).

34. *The Machining of Copper and its Alloys.* A practical handbook with illustrations, summarising modern practice and giving guidance on the selection of copper alloys for machined products (116 pp.).

36. *Copper and Copper Alloys: Compositions and Mechanical Properties.* A booklet tabulating the compositions and mechanical properties of copper and copper alloys in wrought and cast forms, with references to the appropriate British Standards (28 pp.).

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